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Microplastics in Biosolids: Integrating Environmental Risk Assessment into Sustainability Engineering Education

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Abstract

The land application of biosolids derived from wastewater treatment plants is widely practiced as a nutrient recycling strategy in agricultural systems. However, increasing evidence demonstrates that biosolids contain emerging contaminants, including microplastics (MPs), which may pose ecological and human health risks. Although wastewater treatment effectively removes a substantial fraction of MPs from influent, these particles accumulate in sewage sludge and are subsequently introduced into agricultural soils through land application. Despite growing documentation of their occurrence, fate, and potential impacts, comprehensive environmental risk assessment (ERA) frameworks remain insufficiently integrated into biosolids management and agricultural sustainability evaluation.

This opinion paper advances two central arguments. First, it synthesizes existing literature to evaluate a conceptual ERA framework for biosolid-borne MPs, structured around hazard identification, exposure assessment, toxicity assessment, and risk characterization. Second, it argues that sustainability engineering education must embed emerging contaminant risk frameworks into curricula to prepare graduates capable of addressing plastic pollution challenges within agricultural and circular economy systems. A newly developed curriculum incorporating problem-based learning (PBL), minute papers, and a gamified ERA-based group project is presented as a replicable educational model. Linking ERA research with curriculum innovation is essential for developing employment-ready professionals equipped to mitigate plastic pollution and its climate implications.

Keywords: Microplastics, Biosolids, Environmental risk assessment, Sustainability engineering education, Circular economy, Agricultural systems

1. Introduction

The rapid expansion of plastic production and consumption has resulted in widespread environmental contamination. Microplastics (MPs), defined as plastic particles smaller than 5 mm, have emerged as contaminants of global concern due to their persistence, mobility, and capacity to interact with ecological and biological systems. Wastewater treatment plants (WWTPs) function as both sinks and redistribution points for MPs. While treatment processes remove a significant fraction of MPs from wastewater, these particles accumulate in sewage sludge that is subsequently processed into biosolids. When biosolids are applied to agricultural soils, MPs are introduced into terrestrial ecosystems.

Recent scholarship has documented the occurrence, spatiotemporal trends, and treatment technologies associated with MPs in biosolids [1]. Reviews have also evaluated mitigation strategies designed to reduce microplastic contamination before land application, including source reduction and advanced treatment technologies [2]. However, international biosolids management frameworks have historically focused on pathogens, heavy metals, and nutrient balances, with limited integration of microplastics into formal quality and risk management systems [3].

The agricultural reuse of biosolids aligns with circular economy principles, promoting nutrient recovery and reducing waste disposal burdens [4]. Yet sustainability must encompass contaminant risk evaluation. Evidence suggests that MPs may alter soil microbial communities, influence rhizosphere processes, and potentially transfer through food chains [5,6]. The absence of structured environmental risk assessment (ERA) frameworks specific to biosolid-borne MPs complicates regulatory decision-making and agricultural management. This paper argues that effective management of MPs in biosolids requires both scientific advancement in ERA methodologies and educational reform to prepare engineers and agricultural professionals capable of implementing such frameworks.

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2. Environmental Risk Assessment Framework for Biosolid-Borne Microplastics

Environmental risk assessment provides a systematic methodology for evaluating adverse ecological and human health effects. Recent research has proposed ecological risk assessment frameworks tailored to agricultural soils amended with biosolids containing MPs [7]. Building upon these models, ERA for biosolid-borne MPs can be structured into four interdependent stages: hazard identification, exposure assessment, toxicity assessment, and risk characterization.

2.1. Hazard Identification

Hazard identification determines whether MPs possess intrinsic properties capable of causing harm. Microplastics exhibit diverse polymer types, particle sizes, morphologies, and additive compositions. Sewer pipe materials and industrial trade waste streams contribute to MP profiles in biosolids [8]. In addition to physical properties, MPs may sorb organic pollutants and metals during wastewater treatment [1], increasing potential hazard complexity. Experimental studies demonstrate that biosolid-derived MPs may affect rhizosphere respiration and plant–soil biochemical interactions, as shown in Glycine max systems [5]. Such findings indicate that hazard identification must account for both direct toxicity and indirect ecological disruption.

2.2. Exposure Assessment

Exposure assessment evaluates the magnitude and duration of contact between receptors and MPs. Concentrations of MPs in biosolids, application rates, soil characteristics, and environmental conditions influence exposure levels. Reviews of microplastic occurrence and treatment technologies emphasize variability in concentrations and highlight the need for harmonized analytical methodologies [1]. Microbial community shifts in biosolids-amended soils, documented using high-throughput sequencing techniques [6], suggest ecological exposure pathways beyond direct particle ingestion. Human exposure may occur via crop uptake, trophic transfer, or incidental soil ingestion. Comprehensive cross-media risk assessments underscore the need to consider cumulative exposure across environmental compartments [9].

2.3. Toxicity Assessment

Toxicity assessment examines biological responses to exposure. MPs may induce adverse effects through physical obstruction, oxidative stress, or release of chemical additives. Ecological risk frameworks tailored to agricultural soils stress the importance of evaluating chronic and sublethal endpoints [7]. However, translating laboratory findings to field-scale agricultural systems remains challenging.

2.4. Risk Characterization

Risk characterization integrates hazard, exposure, and toxicity data to estimate overall risk magnitude and uncertainty. Existing biosolids risk management frameworks emphasize precautionary approaches but rarely include MPs explicitly [3]. Circular economy analyses highlight the need to balance nutrient recovery benefits with contaminant risks [4]. Robust risk characterization requires interdisciplinary data integration and adaptive management strategies.

3. Implications for Agricultural Sustainability

Biosolids application enhances soil fertility and supports circular nutrient economies. Nevertheless, sustainability assessments must incorporate emerging contaminants such as MPs.

Evidence of altered microbial communities and rhizosphere respiration suggests potential long-term soil health implications [5,6]. Mitigation strategies, including improved wastewater treatment technologies and upstream plastic reduction, have been Proposed [2], yet lifecycle evaluations are needed to assess environmental trade- offs comprehensively.

4. Integrating Environmental Risk Assessment into Sustainability Engineering Education

Scientific understanding alone is insufficient to address plastic contamination in agricultural systems. Educational reform is necessary to prepare professionals capable of implementing ERA frameworks and sustainable management strategies. A plastics assessment course was developed that integrates problem-based learning (PBL), minute papers, and gamified group projects centered on ERA. The curriculum is structured around three pillars: plastic waste management, alternatives to plastics, and analysis and risk assessment. This structure mirrors the ERA process and ensures alignment between scientific analysis and sustainable design. To cultivate analytical and critical thinking skills, structured PBL and minute paper exercises were incorporated into the course. Table 1 presents representative examples of these instructional tools.

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Sample PBL Questions	Sample Minute Paper Questions
Q1. Present and discuss a step-by-step process for assessing the environmental risks of micro-/nanoplastics (MNPs). **Q2.** Present and discuss the issues associated with assessing the toxicity of plastic products. **Q3.** Illustrate and discuss the correlation between the characteristics of MNPs and toxicity impacts on the human body. **Q4.** Present and discuss the benefits and risks of remediation methods for plastic pollution cleanup. **Q5.** Present and discuss factors affecting the ultimate fate of MNPs in the environment.	**Q1.** Briefly summarize the reference paper and suggest methods for controlling the sources of microplastics accumulated at wastewater treatment plants. **Q2.** Briefly summarize the reference paper and present the challenges in predicting plastic pollution. **Q3.** Briefly summarize the reference paper and illustrate potential health impacts of MNPs released from food production. **Q4.** Briefly summarize the reference paper and describe the effects of biofouling on the fate of MNPs. **Q5.** Briefly summarize the reference paper and describe potential barriers to applying biodegradation of microplastics.

Table 1: Sample Problem-Based Learning (PBL) and Minute Paper Questions Used to Reinforce Environmental Risk Assessment Concepts

The PBL questions encourage students to construct ERA frameworks, evaluate toxicity limitations, and analyze remediation trade-offs. The minute paper exercises promote concise synthesis of peer-reviewed literature, reinforcing active engagement with contemporary research on microplastics and biosolids.

In addition to written exercises, a semester-long gamified group project was implemented to simulate real-world decision-making. Students assumed stakeholder roles, including manufacturer, consumer, regulator, and waste manager. The project required integration of lifecycle thinking, material selection, and environmental risk assessment. Table 2 outlines the structure of this gamified ERA project. The gamified structure increased student engagement while reinforcing quantitative reasoning and systems thinking.

By integrating ERA into material selection and lifecycle decisions, students experienced firsthand the trade-offs inherent in circular economy strategies. Program success was evaluated through employment outcomes, industry partnerships, publications, internships, and patents. Continuous feedback from industry surveys informed curriculum updates, ensuring alignment with workforce needs and emerging environmental challenges.

Week / Round	**Objectives**	**Activities**	**Gamified Elements Feedback**	**Deliverables**
Round 1: Introduction & Group Formation	Understand project goals and plastics impacts	Kickoff lecture; overview of plastics trade-offs; introduction to scoring; group formation and role assignment; distribution of lifecycle tools	N/A	Group roster; research plan with objectives and implementation strategy
Round 2: Material Selection	Select plastics or alternatives	Evaluate PET, PLA, recycled and biodegradable materials; assess sustainability and feasibility	Leaderboard scoring based on sustainability metrics	Decision log; justification; environmental and economic impact report including ERA
Round 3: Production & Lifecycle Decisions	Determine production and end-of-life strategies	Simulate production efficiency; recycling strategies; incorporate consumer behavior	Leaderboard updates; surprise regulatory events	Updated decision log; summary report

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Round 4: Presentation & Reflection	Evaluate outcomes and reflect	Final presentation including lifecycle impacts; peer evaluation	Sustainability and innovation badges awarded	Final report; reflection; presentation

Table 2: Gamified Group Project Incorporating Environmental Risk Assessment (ERA) into Sustainability Decision-Making

5. A Replicable Model for Agricultural and Environmental Education

Integrating ERA of MPs into sustainability engineering curricula offers a replicable model for environmental and agricultural programs. Aligning research, industry engagement, and experiential learning strengthens workforce readiness and supports proactive management of emerging contaminants. As agricultural systems increasingly incorporate circular economy ractices, professionals must possess competencies in contaminant risk evaluation alongside nutrient management. Embedding ERA into engineering and agricultural education ensures that sustainability claims are grounded in scientific rigor.

6. Conclusion

Microplastics in biosolids represent a complex sustainability challenge at the intersection of wastewater treatment, agriculture, and public health. While biosolid reuse supports nutrient recovery and circular economy goals, emerging contaminant risks necessitate structured environmental risk assessment. Recent literature emphasizes mitigation technologies, ecological impact studies, and comprehensive risk frameworks [1-9]. Equally important is educational innovation. The integration of ERA-based PBL exercises and gamified projects demonstrates how sustainability engineering education can prepare students to address plastic pollution and its climate implications. Embedding environmental risk assessment into agricultural and engineering curricula is therefore both a scientific necessity and an educational imperative.

Author contributions

SHJ: Conceptualization, development of the role-playing gamification pedagogy, original draft preparation, review, and editing.

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Conflict of Interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Generative AI Statement

The author declares that no generative artificial intelligence tools were used in the preparation of this manuscript.

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